

Inadequate documentation in published life cycle energy reports on buildings

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Received: 23 July 2009 / Accepted: 1 June 2010 / Published online: 12 June 2010
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Abstract

Purpose Over the past two decades, energy efficiency of building operation has increased significantly. As a result, the percentage of building life cycle energy attributed to embodied energy has also risen. This percentage, as measured in recent LCA studies, ranges between 2% and 51% and is influenced by the different climatic, infrastructure, and building characteristics that comprise the input data for these studies. Comparing the results of these studies is helpful in understanding how different combinations of these characteristics influence the relative proportions of embodied and operational energy. However, results are also influenced by the subjectivity inherent in each LCA study. Thus, meaningful comparison of results requires documentation of study methodologies, as outlined in ISO 14041.

Methods In this paper, 20 journal articles describing LCA studies of buildings were reviewed for their adherence to key ISO 14041 documentation requirements.

Results It was found that the majority of journal articles have inadequate documentation.

Conclusions Journal articles are not subject to ISO 14041 requirements and, due to limitations in article length, some degree of documentation is necessarily omitted. However, since journal articles provide much of the publicly available data on the life cycle energy of buildings, a minimum degree of documentation should be provided to allow comparison between LCA results, without substantially increasing article length. Recommended documentation for

journal articles that describe LCA studies of buildings, as proposed in this paper, includes: a list life cycle stages and unit processes included within the system boundary; a statement of calculation procedure; and the referencing of all data sources.

Keywords Buildings · Documentation · Embodied energy · ISO 14041 · Life cycle assessment

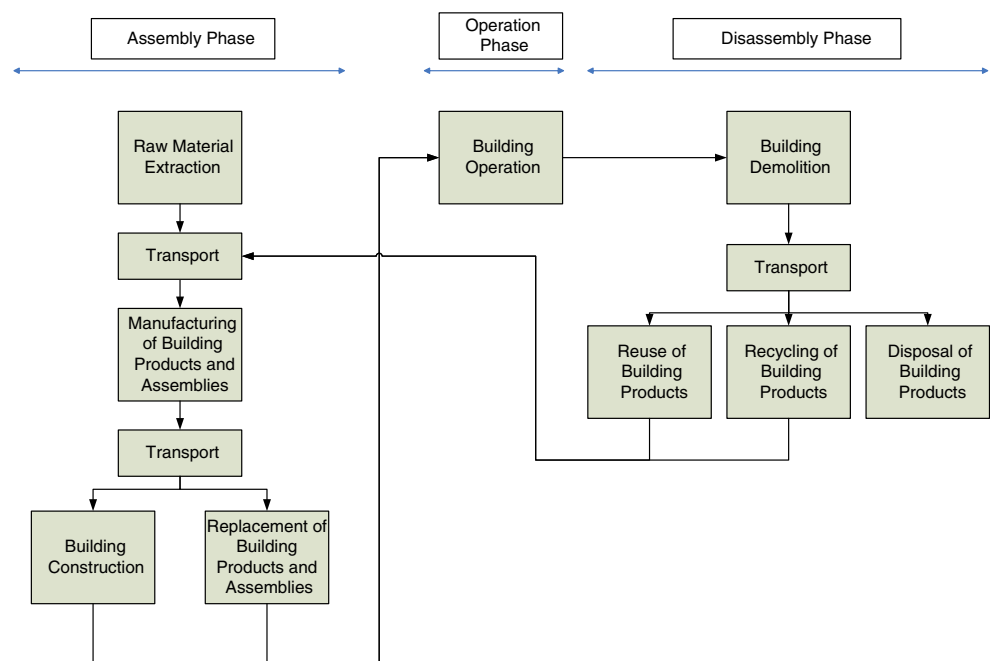
1 Background, aim, and scope

1.1 Life cycle assessment for buildings

A typical building life cycle can be broken into three distinct phases each consisting of one or several life cycle stages, as illustrated in Fig. 1. The assembly phase refers to the collection of raw materials through resource extraction or recycling, the manufacture of these raw materials into building materials, building construction, the replacement of building materials, and intermediate transportation steps. The operation phase refers to heating and electricity requirements, water services, and other services excluding the replacement of building materials. The disassembly phase refers to the decommissioning and demolition of the building, the disposal/recycling/reuse of building materials, and intermediate transportation steps.

There are tens to hundreds of different materials in a building which can be considered in an LCA study. Consequently, there are many and diverse unit processes to consider—ranging from the mining of gypsum, the transport of steel, consumption of diesel by construction equipment, electricity load of a steel recycling facility, and many others. The choice of life cycle stages and unit

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Fig. 1 Life cycle of a building

processes for inclusion within the system boundary depends on the goal of the LCA practitioner and the scope of the study.

LCA studies of buildings can be conducted to determine all or part of the life cycle energy of a building. This life cycle energy includes three components: embodied energy, operational energy, and disposal energy, as described in Table 1. In most cases, operational energy is the largest component, followed by embodied energy. Disposal energy is always minimal.

Over the past two decades, rising energy costs, increasing energy demand, energy supply concerns, and the prospect of climate change have led to increasing efforts to improve the energy efficiency of buildings. To date, efforts have focused principally on operational energy, where strategies have included demand side management techniques, increased insulation in the building envelope, and increased efficiency of lighting, heating, ventilation, and air conditioning systems. Improvements in operational energy efficiency as a result of these efforts have been

substantial. In Canada, for example, residential space heating efficiency increased 18% between 1990 and 2005 (Natural Resources Canada 2008).

As operational energy efficiency increases, the proportion of the life cycle energy of a building attributed to embodied energy increases. In some cases, increased operational energy efficiency requires additional embodied energy, as in the use of additional insulation materials.

The percentages of embodied and operational energy of a building vary depending on climate, local infrastructure, and building characteristics. More specifically, these percentages will depend upon a large number of variables, including: outdoor temperature, types of fuels used for heating and electricity generation, proximity to regional centers, building life span, building use, structure and envelope types, material replacement schedules, occupancy levels, types of heating system technologies, recycled or reused material content, and insulation levels. Different combinations of these variables results in different relative percentages of embodied and operational energy.

Table 1 Life cycle energy components of a building

Component	Description	Percentage of life cycle energy ^a	Frequency of inclusion in LCA studies
Embodied energy	Energy consumed in the assembly phase	2–51%	Always measured
Operational energy	Energy consumed in the operation phase (i.e., electricity and heating loads)	46–97%	Often measured
Disposal energy	Energy consumed in the disassembly phase	1–3%	Seldom measured

^a Refer to Table 2 for a list of data sources

Table 2 Literature review, embodied to annual operational energy ratio

Author	Building life (years)	Embodied energy (% of life cycle energy)	Operational energy (% of life cycle energy)	Ratio of embodied to annual operational energy
Blanchard and Reppe 1998	50	6	94	3
Cole and Kernan 1996	50	11–18	82–89	6–11
Fay et al. 2000	25	39	61	16
	50	31	69	23
	75	28	72	29
	100	25	75	33
	35	8–19	71–92	3–9
Li 2006	35	8–19	71–92	3–9
Scheuer et al. 2003	75	2	98	2
Thormark 2002	50	40	60	33
Yohanis and Norton 2002	25	51	49	26
	50	45	55	50
	100	42	58	72

A number of recent studies provide data on the relative contributions of embodied and operational energy to life cycle energy, as shown in Table 2. In these studies, embodied energy varies between 2% and 51% of total life cycle energy, while operational energy varies between 49% and 98%. A useful metric to compare studies is the ratio of embodied to annual operational energy. As shown in Table 2, embodied energy varies between 2 and 72 years equivalent of annual operational energy. This large range highlights the importance of extending the concept of a building's energy efficiency to include the embodied energy component. By focusing only on operational energy improvements, significant opportunities to increase the life cycle energy efficiency of a building can be missed.

1.2 Subjectivity in LCA studies

Each LCA study uses a unique methodology based on the specific goal and scope of the study as determined by the LCA practitioner. Consequently, methodologies may vary substantially and can have significant impact on study results. To enable interpretation of results and allow comparisons between studies, the LCA practitioner must provide sufficient documentation of methodology in the LCA report. Required documentation is described in ISO 14041—Life Cycle Assessment—Goal and Scope Definition and Inventory Analysis.

There are three key components of an LCA methodology that have a significant impact on the calculated life cycle energy of a building and, more specifically, on its embodied and operational energy components: system boundary definition, choice of calculation procedures, and choice of data sources. These components are summarized in the following subsections.

1.2.1 System boundary

The system boundary establishes the life cycle stages, unit processes, and mass/energy flows between unit processes to be included within the product system. Depending on the goal and scope of a study and data availability, elements of the system boundary may be omitted from analysis. Such omissions are commonplace for LCA studies on buildings given the large number of life cycle stages, unit processes, and flows one can consider.

Entire physical components of a building can also be omitted from the system boundary. Though the building structure and envelope are almost always included, the mechanical systems and interior finishing are almost always excluded. This has significant impact on embodied energy. In one study, the inclusion of mechanical systems and interior finishing within the system boundary nearly tripled the embodied energy of the building (Suzuki and Oka 1998).

The extent to which the inputs into unit processes are traced back to upstream unit processes is another important consideration. Consider the embodied energy of cement as an example. In the simplest case, the practitioner would reference the embodied energy of cement from a report. Alternatively, the practitioner may use that report to determine the inputs into cement production and then include additional unit processes based on those inputs into the system boundary of the building (e.g., limestone mining, processing of natural gas, etc.). The practitioner could proceed further, if desired, and include upstream unit processes to limestone mining and natural gas processing (e.g., diesel production, natural gas extraction, etc.). As more upstream unit processes are included within the system boundary of the building, additional fuel and

Table 3 Literature review of adherence to ISO 14040 criteria

	List of included and excluded life cycle stages	Unit processes included in each life cycle stage	Statement of calculation procedure	Data source referenced
Adalberth 1997	Yes	Yes	N/A	Yes
Blanchard and Reppe 1998	Yes	No	No	Yes
Borjesson and Gustavsson 2000	Yes	No	No	Yes
Cole 1998	Yes	Yes	N/A	Yes
Cole and Kernan 1996	Mostly indicated	No	No	No
Dong et al. 2005	Mostly indicated	No	No	Yes
Fay et al. 2000	Yes	No	Yes	No
Gerilla et al. 2007	Partly indicated	No	Yes	Yes
Gonzalez and Navarro 2006	No	No	No	Yes
Gustavsson and Sathre 2006	Mostly indicated	No	No	Yes
Hacker et al. 2008	No	No	No	Yes
Li 2006	Mostly indicated	No	No	Yes
Mithraratne and Vale 2004	No	No	No	Yes
Scheuer et al. 2003	Yes	Yes	No	Yes
Sinivuori and Saari 2006	Yes	No	No	Yes
Suzuki and Oka 1998	Partly indicated	No	Yes	Yes
Thormark 2002	Mostly indicated	No	No	No
Thormark 2006	Mostly indicated	No	No	No
Yohanis and Norton 2002	Yes	No	Yes	Yes
Zhang et al. 2006	Mostly indicated	No	No	Yes

electricity inputs are also included, thus increasing the embodied energy of cement.¹

Given the various sources of subjectivity within the system boundary of a building, the LCA practitioner must ensure that “the criteria and the assumptions on which [system boundaries] are established [are] clearly described” and that “any decision to omit life cycle stages, processes or inputs/outputs [is] clearly stated and justified” (ISO 1998).

1.2.2 Calculation procedures

In this paper, the term “calculation procedure” refers specifically to the mathematical process or framework used to calculate environmental impacts from a given set of unit processes and flows. There are several different calculation procedures that can be used by the practitioner. These include process flow diagrams, process-based matrix representation of product system, input–output (IO)-based LCI, and three distinct types of hybrid analysis that blend components of process- and IO-based LCI (Suh and

Huppes 2005).² Each calculation procedure is unique in the mathematics and data types used to calculate results; thus, results depend on which procedure is used. In one study, embodied energy results for a building using matrix representation differed from results using process flow diagrams and IO-based calculation procedures by 4.0% and 20.5%, respectively (Optis 2008).

The choice of calculation procedure is not explicitly required in ISO 14041 but is inferred: “the models used [to represent the product system] should be described and the assumptions underlying those choices should be identified” (ISO 1998).

1.2.3 Data sources

Typically, there are dozens to hundreds of building materials to consider in an LCA study. It is thus impractical for LCA practitioners to develop data for individual building materials. Rather, the embodied energies of

¹ There is a limit to this increase. With each successive step upstream, the magnitude of fuel and electricity inputs becomes smaller and approaches zero. Thus, embodied energy converges to a single value.

² Data sources used in IO-based LCI are distinct from those used in process-based LCI. In IO-based LCI, economic input–output tables are used to model the economic activity of an aggregated industry as a unit process and to model the monetary exchanges between industries as flows. In process-based LCI, actual physical processes are modeled as unit processes, which are connected by various mass and energy flows.

Table 4 Inclusion and exclusion of life cycle stages

	Extraction of raw materials	Transport to production facility	Manufacture	Transport to building site	Construction	Operation and maintenance	Demolition	Transport of waste streams	Disposal, recycling, or reuse
Adalberth 1997	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Blanchard and Reppe 1998	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Borjesson and Gustavsson 2000	Yes	Yes	Yes	No	No	No	No	No	No
Cole and Kernan 1996	Yes	Not indicated	Yes	Yes	Yes	Yes	Yes	Yes	No
Cole 1998	No	No	No	Yes	Yes	No	No	No	No
Dong et al. 2005	Yes	Not indicated	Yes	Yes	Yes	Yes	Yes	No	No
Fay et al. 2000	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No
Gerilla et al. 2007	Not indicated	Not indicated	Not indicated	Yes	Yes	Yes	Yes	Yes	Not indicated
Gonzalez and Navarro 2006	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated
Gustavsson and Sathre 2006	Yes	Yes	Yes	Yes	No	No	No	Not indicated	Yes
Hacker et al. 2008	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated
Li 2006	Not indicated	Not indicated	Yes	Yes	Yes	Yes	Yes	Yes	No
Mithratne and Vale 2004	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Yes	Not indicated	Not indicated	Not indicated
Scheuer et al. 2003	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sinivuori and Saari 2006	Yes	No	Yes	No	Yes	Yes	No	No	No
Suzuki and Oka 1998	Not indicated	Not indicated	Not indicated	Not indicated	Not indicated	Yes	No	No	No
Thormark 2002	Yes	Not indicated	Yes	Yes	No	Yes	No	Yes	Yes
Thormark 2006	Yes	Not indicated	Yes	Yes	No	Yes	No	Yes	Yes
Yohanis and Norton 2002	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Zhang et al. 2006	Yes	Not indicated	Yes	Yes	Yes	Yes	Yes	Not indicated	Yes

Table 5 Review of documentation in journal articles describing LCA studies of buildings

Criteria	Results
List of included and excluded life cycle stages	60% of the studies do not explicitly state the inclusion or exclusion of each life cycle stage within the system boundary identified in Fig. 1. 25% of the studies do not explicitly state the inclusion or exclusion of four or more life cycle stages identified in Fig. 1 10% do not explicitly state the inclusion or exclusion of any life cycle stage identified in Fig. 1.
List of unit processes included in each life cycle stage	85% of the studies do not identify the unit processes included within the system boundary
Statement of calculation procedure	78% of the studies do not specify the calculation procedure
Referencing of data sources	20% of the studies do not adequately reference data sources

individual building materials are typically referenced from available literature. Many data sources are cited in the reviewed articles. Several of these sources are cited in more than one study, including the Building for Environmental and Economic Sustainability LCI database, the Swedish Center for Environmental Assessment of Product and Material Systems, the US National Renewable Energy Laboratory LCI database, and the Athena Sustainable Materials Institute LCI data.

Referenced data will be subject to the time when and place where data was collected as well as the assumed technologies (ISO 1998). Consequently, referenced data do not usually match the temporal, geographical, or technological conditions of a particular building under study.

Further, data taken from different sources may not be based on equivalent study methodologies. For example, a practitioner may use two different data sources for cement

and steel: one which accounts for intermediate transport of raw materials to a manufacturing facility and one which does not. Thus, the embodied energies for various products in the same building may be difficult to compare.

Due to this variability in data sources, it is required by ISO 14041 that “the published literature which supplies details about the relevant data collection process, the time when data have been collected and about further data quality indicators, shall be referenced” (ISO 1998).

1.3 Documentation in condensed LCA reports

LCA reports on buildings can span hundreds of pages and are often not publicly available. To make results public, practitioners generally present summary results in journal articles. Due to the restrictions on length, these articles highlight only key aspects of the methods and findings.

Table 6 Example documentation for building products and data sources

Building products	Referenced embodied energy	Calculated embodied energy				
		Raw material extraction	Intermediate transport	Manufacture and assembly	Transport to building site	Data source
Structure						
Concrete Foundation	Yes	N/A	N/A	N/A	N/A	Example, 2009
Concrete Columns	Yes	N/A	N/A	N/A	N/A	Example, 2009
Concrete Floor Slabs and Roof	Yes	N/A	N/A	N/A	N/A	Example, 2009
Steel Rebar in Slabs and Beams	No	Yes	No	Yes	No	Example, 2009
Sand and Gravel Backfill	No	Yes	Yes	No	Yes	Example, 2009
Envelope						
Polystyrene Rigid Insulation	No	Yes	No	Yes	No	Example, 2009
Steel Stud Partition Walls	No	Yes	Yes	Yes	Yes	Example, 2009
Gypsum Dry Board	No	Yes	Yes	Yes	Yes	Example, 2009
Window Assemblies	Yes	N/A	N/A	N/A	N/A	Example, 2009
Brick Veneer	No	Yes	Yes	Yes	Yes	Example, 2009
Asphalt roofing	No	Yes	No	Yes	No	Example, 2009
Linoleum Flooring	Yes	N/A	N/A	N/A	N/A	Example, 2009

Table 7 Example documentation for included life cycle stages and unit processes

Life cycle stages	Unit processes
Assembly phase	
Raw material extraction	Fossil fuel consumed by extraction equipment Extraction, manufacturing and delivery of fossil fuel
Intermediate transport	Fossil fuel consumed by transport vehicle Extraction, manufacturing and delivery of fossil fuel
Manufacture and assembly	Fossil fuel and electricity consumed by manufacturing equipment, Heating loads of manufacturing facility Extraction, manufacturing and delivery of fossil fuel Production and delivery of electricity
Transport to building site	Fossil fuel consumed by transport vehicle Extraction, manufacturing and delivery of fossil fuel
Building construction	Not considered
Operation phase	
Building operation	Heating and electric loads of building Extraction, manufacturing and delivery of fossil fuel Production and delivery of electricity
Disassembly phase	Not considered

Consequently, much of the detail of study methodology is necessarily omitted. ISO 14041 does not explicitly address documentation requirements for condensed reports presented as journal articles.

Useful and informed comparisons of the embodied and operational energies of a building require, at a minimum, the following documentation requirements:

- List of included and excluded life cycle stages within the system boundary
- List of unit processes included within the system boundary
- Statement of calculation procedure
- Referencing of data sources

Omitting these key requirements introduces substantial uncertainty in study results. At worst, omitting a list of included unit processes introduces an uncertainty on the order of 100%, as discussed in Section 1.2.1 in the context of Suzuki and Oka (1998). At best, omitting a statement of calculation procedure introduces an uncertainty on the order of 10%, as discussed in Section 1.2.2 in the context of Optis (2008). In either case, the uncertainty is sufficiently large to make comparison between results difficult, if not impossible.

2 Methods

Twenty journal articles describing LCA studies of buildings were identified.³ Each article was reviewed to determine the

presence or absence of the key requirements identified in Section 1.3.

3 Results

Results for each LCA study are shown in Table 3. Detailed results for the list of included and excluded life cycle stages are shown in Table 4. Key findings are summarized in Table 5.

4 Conclusions

Based on the key findings in Table 5, it is concluded that sufficient documentation has not been provided in the majority of published journal articles that describe LCA studies of buildings. Data sources are generally well referenced, and life cycle stages are reasonably well documented. However, unit processes are rarely documented and calculation procedures are rarely stated. Due to this inadequate documentation, it is difficult to compare the embodied and operational energies of buildings presented in these articles. Consequently, these articles are of limited use in disseminating or advancing the practice of LCA as applied to the life cycle energy efficiency of buildings.

Table 8 Example documentation for statement of calculation procedure

Calculation procedure	Matrix representation
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³ An exception is Blanchard and Reppe, 1998, which is a Master's thesis.

Consider, for example, Thormark (2006). In this article, several construction designs for an apartment complex in Southern Sweden are modeled, and the embodied and operational energies of each design are compared. Results of this study would be useful for building designers in reducing the life cycle energy of apartment complexes. However, due to inadequate documentation in the article, building designers would have difficulty interpreting these results. First, unit processes and calculation procedures are not identified, thus, introducing significant uncertainty in results. Second, data sources for the embodied energies of building materials are not referenced. Consequently, the reader cannot investigate what methods were used to calculate embodied energy and cannot verify that the referenced embodied energies are applicable to construction in southern Sweden. Had the article adhered to the minimum documentation requirements proposed in Section 1.3, results could be interpreted with more certainty and would become more useful to building designers.

Tables 6, 7, and 8 present data that satisfies this minimum documentation requirement for a hypothetical building. In Table 6, a clear indication is first made whether embodied energy is simply referenced from a data source or whether embodied energy is calculated using more detailed information from that data source. For the latter case, the specific life cycle stages included in determining embodied energy are stated. In the last column, data sources are listed for each building product. In Table 7, a list of included and excluded life cycle phases and stages is clearly identified, along with unit processes modeled within each. In Table 8, the calculation procedure is stated. The information in Tables 6 through 8 present the key aspects of study methodology and do not substantially increase the length of the journal article.

The articles reviewed in this paper are the first published reports to address the life cycle energy of buildings. These articles have established the foundation for future LCA studies on buildings by identifying the range of system boundaries, calculation procedures, and data sources available to the practitioner. Moreover, results presented in these articles demonstrate the importance of extending the concept of a building's energy efficiency to include the embodied energy component. However, as additional studies on the life cycle energy of buildings are conducted, it is crucial that practitioners provide an improved degree of documentation when publishing results in journals. If documentation remains inadequate, then this growing body of data on the life cycle energy of buildings will be limited in its usefulness.

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